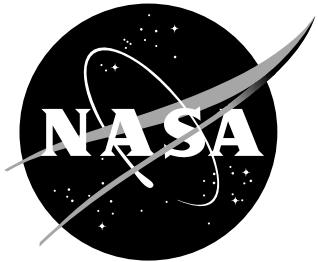


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Fatigue Crack Growth Rate Test Results for Al-Li 2195 Parent Metal, Variable Polarity Plasma Arc Welds and Friction Stir Welds

*Robert A. Hafley, John A. Wagner, and Marcia S. Domack
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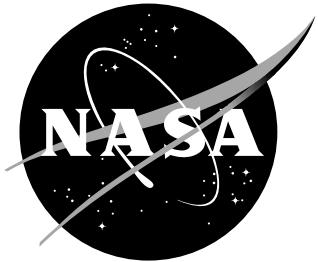
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Abstract

The fatigue crack growth rate of aluminum-lithium (Al-Li) alloy 2195 plate and weldments was determined at 200°F, ambient temperature and -320°F. The effects of stress ratio (R), welding process, orientation and thickness were studied. Results are compared with plate data from the Space Shuttle Super Lightweight Tank (SLWT) allowables program. Data from the current series of tests, both plate and weldment, falls within the range of data generated during the SLWT allowables program.

1. Introduction

The application of advanced aluminum alloys to Reusable Launch Vehicle (RLV) structures required the characterization of the time dependent properties of candidate alloys. The candidate alloy studied in this investigation was aluminum-lithium (Al-Li) alloy 2195. Prior to this investigation, the database which existed for 2195 included strength and fracture data primarily developed for expendable launch vehicle applications. The application of 2195 in RLV systems required the full characterization of the fatigue crack growth rate behavior of both parent and welded 2195 at service temperatures. The thermal profile for RLV structures included ambient temperature, as well as elevated temperatures during ascent and descent, and cryogenic temperatures for oxidizer storage.

2. Symbols and Abbreviations

a	crack length
Al-Li	aluminum-lithium
ASTM	American Society for Testing and Materials
C	normalized K-gradient
C(T)	compact specimen
da/dN	fatigue crack growth rate
ΔK	stress-intensity factor range
FCGR	fatigue crack growth rate
FSW	friction stir welding
F_u	ultimate tensile strength
$F_{0.2y}$	0.2% offset yield strength
HT	heat treatment
K	stress-intensity factor
K_{max}	maximum stress-intensity factor
K_{min}	minimum stress-intensity factor
L	direction parallel to rolling direction
L-T	denotes fracture plane normal to L with propagation in T direction
LN ₂	liquid nitrogen
R	stress ratio
RLV	Reusable Launch Vehicle
SLWT	Super Lightweight Tank
t	thickness
T	direction perpendicular to rolling direction
T-L	denotes fracture plane normal to T with propagation in L direction
VPPAW	variable polarity plasma arc welding
W	specimen width

3. Materials, Specimen and Test Hardware

Fatigue crack growth rate (FCGR) tests were conducted on aluminum-lithium (Al-Li) alloy 2195-T8 plate and weldments. Two gages of plate, 0.25 in. and 0.50 in., were tested in two orientations, L-T and T-L, at 200°F and ambient temperature (~75°F). Weldments of the same gages, prepared by variable polarity plasma arc welding (VPPAW) using Al 4043 filler metal or friction stir welding (FSW), were also tested at 200°F, ambient temperature (~75°F) and/or -320°F.

Compact (C(T)) specimens, Fig.1, were tested per ASTM E647-95a (ref. 1). Plate specimen thickness was the nominal material thickness. Weldment specimen thicknesses were reduced the minimum amount required to ensure that specimen faces were flat and parallel. The machined notch on the weldments was located along the weld centerline. Clevises with flat bottom holes were fabricated per Fig A2.3 in ref. 1. Elevated temperature tests were conducted in an environmental chamber, while specimens were immersed in liquid nitrogen (LN_2) during cryogenic tests.

4. Test Procedure

Tests were conducted in servohydraulic test frames controlled by an automated fatigue crack growth test system. A constant stress ratio, R, of 0.1 or 0.5 was used in all tests. Specimens were fatigue precracked at $\Delta K=10 \text{ ksi}\sqrt{\text{in}}$ from $a/W=0.2$ to $a/W=0.3$. A K-decreasing test was conducted over the range of $\Delta K=10 \text{ ksi}\sqrt{\text{in}}$ to $5 \text{ ksi}\sqrt{\text{in}}$ in order to obtain near-threshold crack growth rates. Tests were conducted using a constant K-gradient, C, of -2 in order to eliminate effects of prior loading on the K-decreasing portion of the test. A K-increasing test was then conducted from a $\Delta K=5 \text{ ksi}\sqrt{\text{in}}$ until instrumentation ranges were exceeded. At the conclusion of the tests, the specimens were fractured to permit examination of the fracture surface and measurement of the final crack length. Data analysis was conducted in compliance with ref.1.

5. Results

Typical mechanical properties for Al2195-T8 plate and weldments are presented in Table 1(ref. 2, plate and private communication, weldments). FCGR results are presented in Tables 2-15 and Figures 2-15, are summarized in Table 16 at selected levels of stress intensity and compared with data from the Space Shuttle Super Lightweight Tank (SLWT) design allowables program (ref. 2) in Table 17.

5.1 Plate

Two thicknesses of 2195 plate, 0.25 in. and 0.50 in., were tested in two orientations, L-T and T-L, at two temperatures, 200°F and 75°F, and two stress ratios, R=0.1 and 0.5. Results of the FCGR tests illustrating the effects of temperature are presented in Table 2 and Figure 2 for 0.25 in. plate and Tables 6-7 and Figures 6-7 for 0.50 in. plate. The effect of stress ratio on the FCGR is shown in Table 3 and Figure 3 for 0.25in. plate and in Tables 4-5 and Figures 4-5 for 0.5 in. plate. The effect of thickness on the FCGR in 2195 plate is illustrated in Tables 8-9 and Figures 8-9. There appears to be little effect of orientation, thickness or test temperature on the FCGR, however increasing the stress ratio from 0.1 to 0.5 does increase the FCGR.

5.2 Variable Polarity Plasma Arc Welds

Variable polarity plasma arc welds of 0.25 in. plate were tested at 75°F with R=0.1 and 0.5. Results of the FCGR tests are presented in Table 10 and Figure 10. There was a significant effect of R on FCGR. At R=0.1, crack growth data could not be generated at or below $\Delta K=10 \text{ ksi}\sqrt{\text{in}}$, presumably due to

residual stresses. Data was obtained at $\Delta K=10$ ksi $\sqrt{\text{in}}$ and an R of 0.5. At $\Delta K=20$ ksi $\sqrt{\text{in}}$, the FCGR at R=0.5 is two orders of magnitude higher than at R=0.1.

Table 1. Typical Mechanical Properties for Al 2195-T8 Plate and Weldments

Temp., °F	Prop.	Orient.	Plate ¹		VPPAW ²	FSW ²	
			0.25 in.	0.5 in.	0.25 in.	0.25 in.	0.5 in.
200	Fty, ksi	L	66	66	—	—	—
		T	62	62	—	—	—
	Ftu, ksi	L	68	68	—	53	—
		T	65	65	—	—	—
75	Fty, ksi	L	84	85	—	39	35
		T	80	80	—	—	—
	Ftu, ksi	L	89	89	52	60	57
		T	86	86	—	—	—
-320	Fty, ksi	L	96	94	—	—	—
		T	92	91	—	—	—
	Ftu, ksi	L	108	107	—	75	—
		T	102	104	—	—	—

1. Ref. 2

2. Private communication

5.3 Friction Stir Welds

Friction stir welds of 0.25 in and 0.50 in plate were tested at 200°F, 75°F and/or -320°F at R=0.5. Results of the FCGR tests at ambient temperature are presented in Table 11 and Figure 11 for 0.25 in. welds and Table 14 and Figure 14 for 0.5 in. welds; cryogenic temperature results are presented in Table 12 and Figure 12 for 0.25 in. welds and Table 15 and Figure 15 for 0.5 in. welds; elevated temperature results are presented in Table 13 and Figure 13 for 0.5 in. welds. There does not appear to be any effect of thickness on the FCGR of Friction Stir Welds. However, the FCGR increases for tests conducted at 200°F and -320°F, compared to tests conducted at 75°F.

6. Discussion

The FCGR of Al-Li 2195-T8 plate and weldments at three selected levels of ΔK , 6, 10 and 20 ksi $\sqrt{\text{in}}$, for each specimen tested is shown in Table 16. Results from replicate specimens of 2195-T8 plate show excellent agreement. Tests conducted on weldments exhibit more scatter, possibly due to residual stress effects from the welding process.

The FCGR of the VPPAW material at a stress ratio of 0.1 is significantly lower than that of the Al-Li 2195-T8 plate at a comparable stress intensity. At a stress ratio of 0.5 and a stress intensity of 10 ksi $\sqrt{\text{in}}$, the FCGR of the VPPAW material is lower than that of the Al-Li 2195-T8 plate. However, at a stress ratio of 0.5 and a stress intensity of 20 ksi $\sqrt{\text{in}}$ the FCGR of the VPPAW material is significantly higher than that of the Al-Li 2195-T8 plate. The FCGR of the FSW material is slightly higher than that of Al-Li 2195-T8 plate at similar stress ratios and stress intensities. This may be attributable to the low residual stress due to welding. These differences in rates for VPPAW material and FSW material as compared to plate may reflect differences in the level of residual stresses resulting from the two welding processes.

The results of this study are summarized in Table 17, along with data from the SLWT design allowables program. All data generated in this program falls to the low end of the broad range of room temperature FCGR data from the SLWT design allowables program. The broad range of data from the

SLWT design allowables can be accounted for by the different material thicknesses tested, 0.25 in. and 1.5 in., the inclusion of short transverse test specimen orientations, S-T and T-S, and testing several different production lots of material.

7. Conclusions

The FCGR of FSW Al-Li 2195-T8 plate is similar to that of unwelded Al-Li 2195-T8 plate at similar stress intensities and stress ratios.

The FCGR of VPPAW Al-Li 2195-T8 plate is lower than that of unwelded Al-Li 2195-T8 plate at similar stress ratios and stress intensities below 10 ksi $\sqrt{\text{in}}$. At stress intensities above 10 ksi $\sqrt{\text{in}}$, the FCGR of VPPAW Al-Li 2195-T8 plate is higher than that of unwelded Al-Li 2195-T8 plate.

8. References

1. Standard Test Method for Measurement of Fatigue Crack Growth Rates. ASTM Designation: E 647-95a, Volume 03.01 of the *1997 Annual Book of ASTM Standards*, 1997, pp. 557-593.
2. Reimuller, R. E., SO 89818 Al-Li Materials Database, Lockheed Martin Manned Space Systems, New Orleans, LA 70189.

Figure 1. C(T) Specimen Design

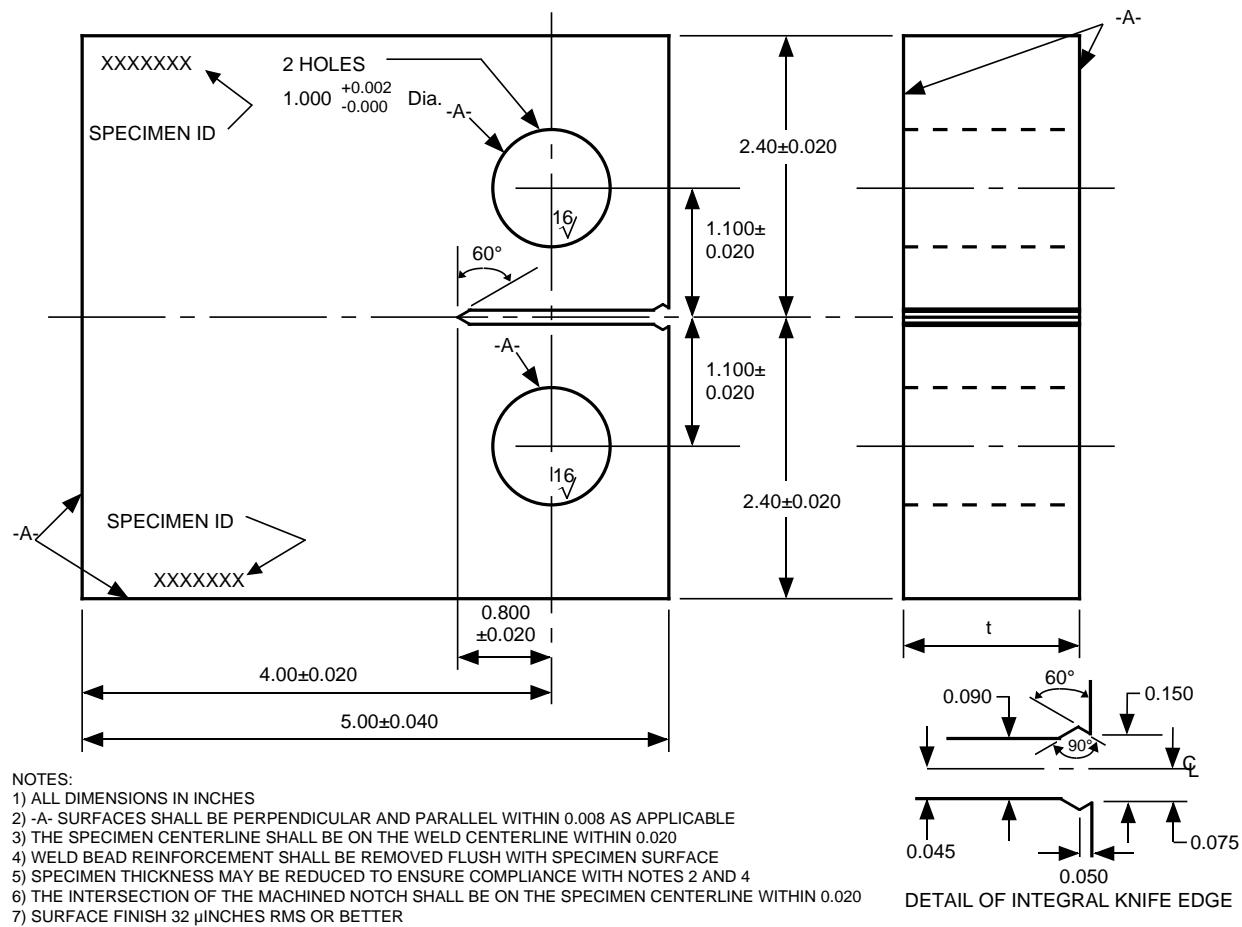


Table 2. Effect of Temperature on the Fatigue Crack Growth Rate in 0.25 in. AL-Li 2195-T8 Plate in the L-T Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 2 Indicating Effect of Temperature

Material: Aluminum 2195

Condition: T8

Environment: Lab Air

Stress Ratio (R): 0.1

ΔK (ksi/in)	(a) P25LT1	da/dN (10^{-6} in/cycle)	
		(c) P25LT2	(d) P25LT3
		75°F	200°F
ΔK_{\min}	5.15	0.24	
	5.16		0.24
	5.15		0.23
ΔK (ksi/in)	6.00	0.42	0.43
	7.00	1.09	1.20
	8.00	2.10	2.24
	9.00	2.57	3.59
	10.00	3.91	5.33
	11.00	5.86	7.00
	12.00	7.68	9.02
	13.00	10.19	11.33
	14.00	12.05	13.63
	15.00	14.22	15.47
	16.00	16.87	17.95
	17.00	20.38	19.82
	18.00	22.91	22.50
	19.00	26.54	24.89
	20.00	30.70	28.20
ΔK_{\max}	24.07	45.13	
	24.09		40.34
	24.08		52.01

Figure 2. Effect of Temperature on the Fatigue Crack Growth Rate in 0.25 in. AL-Li 2195-T8 Plate in the L-T Orientation

CONDITION/HT: T8

FORM: 0.25 in. thick plate

SPECIMEN TYPE: C(T)

ORIENTATION: L-T

FREQUENCY: 15 HZ

ENVIRONMENT: Lab Air

STRESS RATIO (R): 0.1

SPECIMEN THICKNESS: 0.285-0.286 in.

SPECIMEN WIDTH: 4.002-4.003 in.

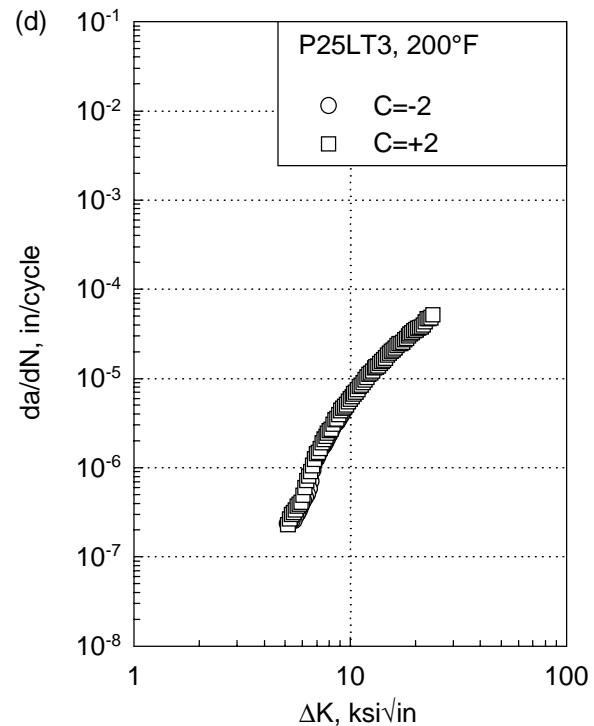
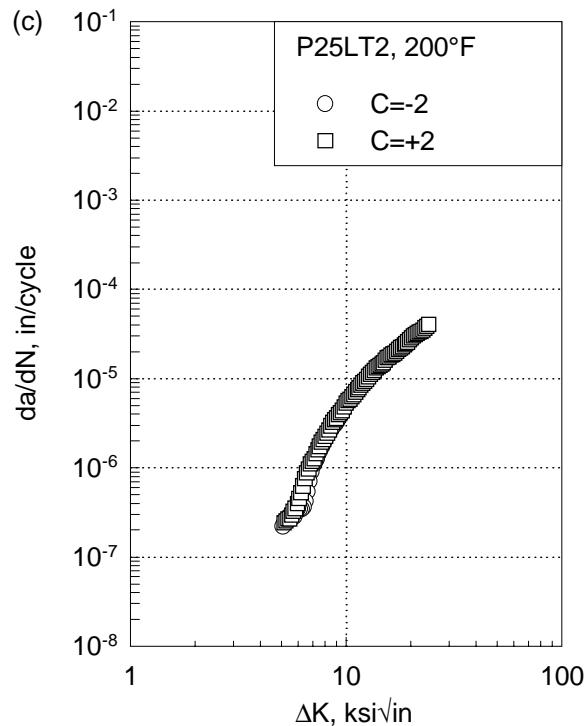
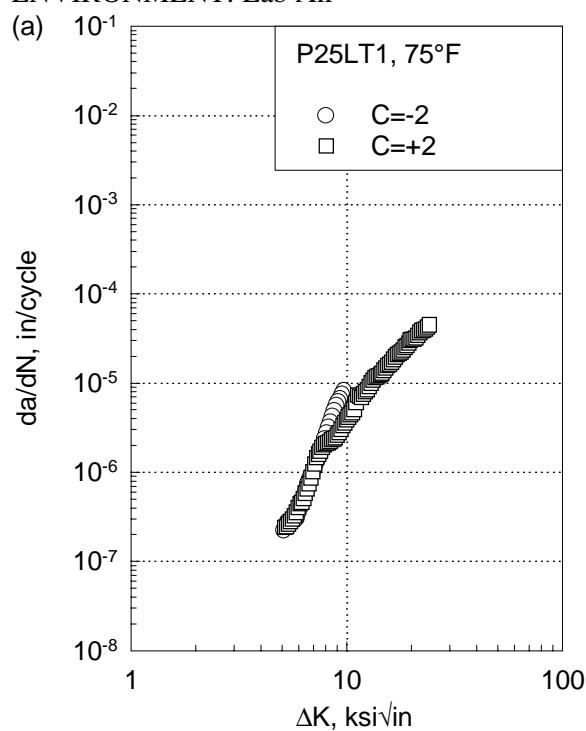


Table 3. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.25 in. AL-Li 2195-T8 Plate in the T-L Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 3 Indicating Effect of Stress Ratio

Material: Aluminum 2195

Condition: T8

Environment: 200°F, Lab Air

ΔK (ksi $\sqrt{\text{in}}$)	da/dN (10^{-6} in/cycle)			
	(a) P25TL5	(b) P25TL6	(c) P25TL7	(d) P25TL8
	R=0.1	R=0.1	R=0.5	R=0.5
ΔK_{\min}	5.07	0.21		
	5.06		0.18	
	5.16			3.31
	5.16			3.78
ΔK	6.00	0.26	0.31	1.09
	7.00	0.51	0.48	2.73
	8.00	1.75	1.02	4.47
	9.00	3.03	1.98	6.52
	10.00	4.51	2.80	1.36
	11.00	5.65	3.97	2.69
	12.00	7.63	5.21	4.40
	13.00	9.94	6.67	
	14.00	12.04	8.18	
	15.00	15.11	10.32	
ΔK_{\max}	16.00			
	17.00			
	18.00			
	19.00			
	20.00			
	15.98	17.37		
	15.14		10.66	
	9.99			8.95
	9.41			7.36

Figure 3. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.25 in. AL-Li 2195-T8 Plate in the T-L Orientation

CONDITION/HT: T8

FORM: 0.25 in. thick plate

SPECIMEN TYPE: C(T)

SPECIMEN THICKNESS: 0.270-0.271 in.

ORIENTATION: T-L

SPECIMEN WIDTH: 4.001 in.

FREQUENCY: 15 HZ

ENVIRONMENT: 200°F, Lab Air

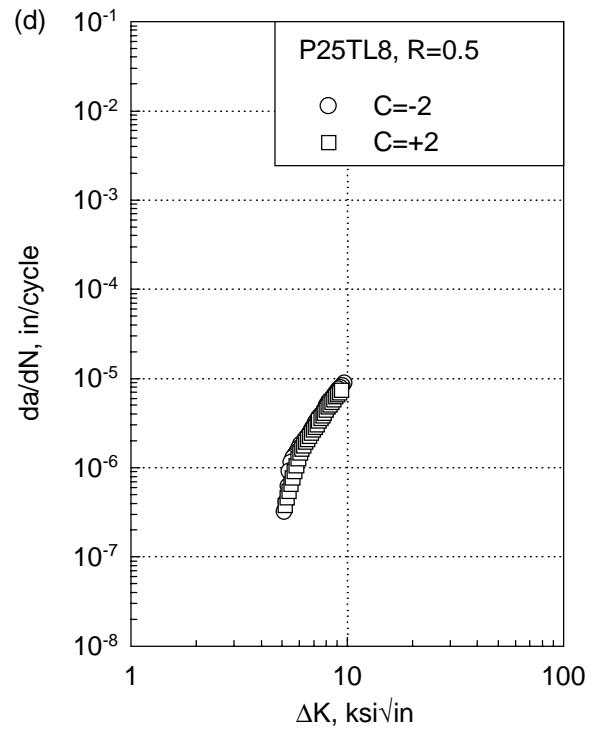
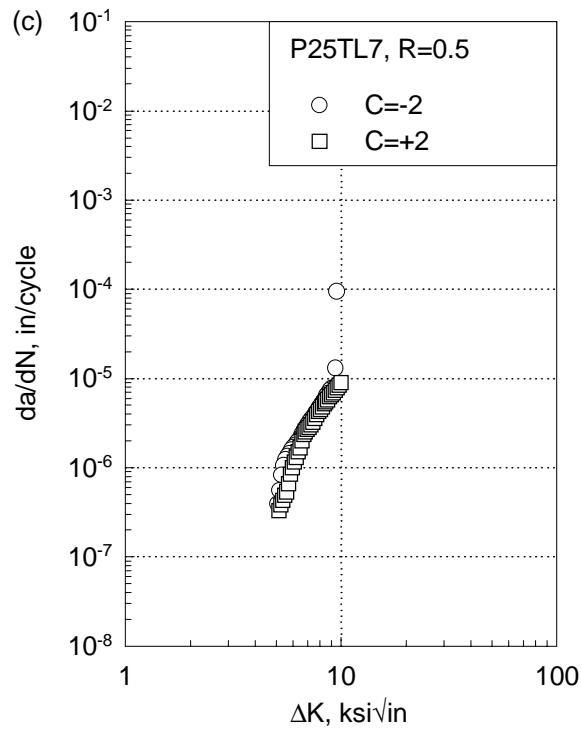
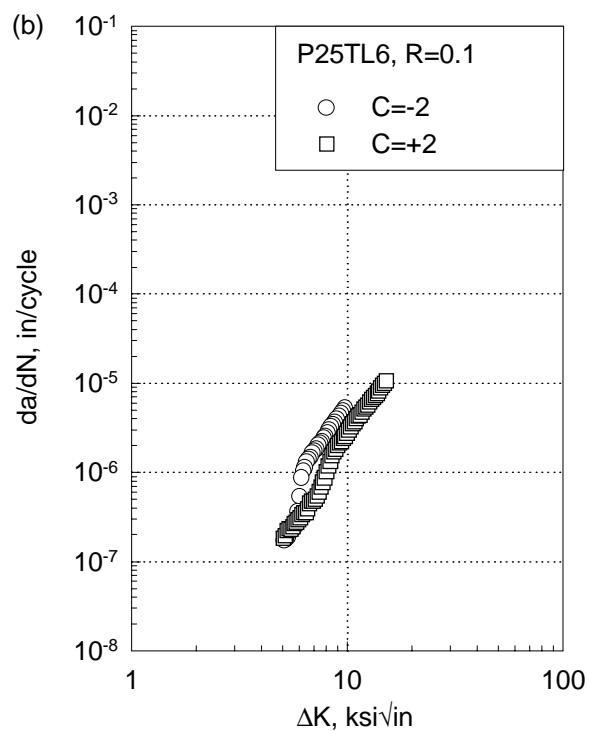
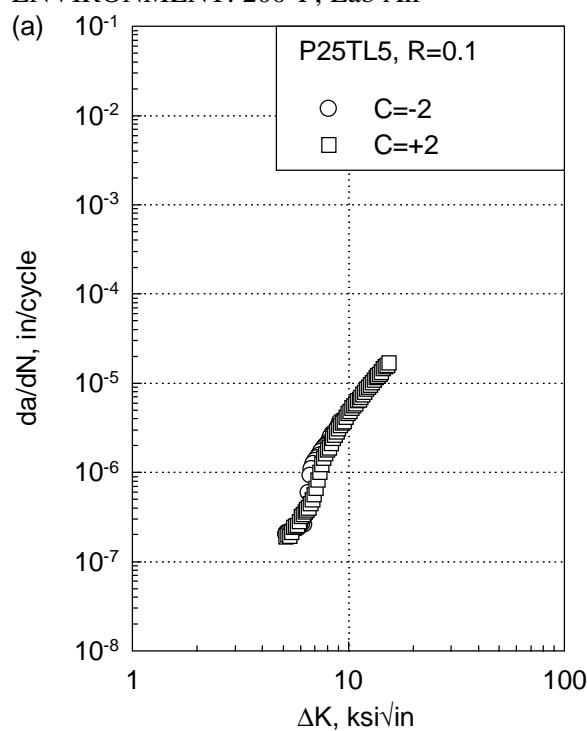


Table 4. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the L-T Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 4 Indicating Effect of Stress Ratio

Material: Aluminum 2195

Condition: T8

Environment: 200°F, Lab Air

ΔK (ksi $\sqrt{\text{in}}$)	da/dN (10^{-6} in/cycle)		
	(a) P50LT1	(b) P50LT2	(c) P50LT3
	R=0.1	R=0.1	R=0.5
ΔK_{\min}	5.48	0.24	
	5.16		0.16
	5.16		0.27
ΔK (ksi $\sqrt{\text{in}}$)	6.00	0.33	0.25
	7.00	0.62	0.41
	8.00	1.82	1.10
	9.00	3.21	2.21
	10.00	4.67	3.42
	11.00	6.41	5.05
	12.00	8.59	7.30
	13.00	10.55	8.68
	14.00	13.38	10.96
	15.00	15.83	13.31
	16.00	19.92	17.50
	17.00	21.23	19.51
	18.00	24.53	22.21
	19.00	26.27	24.53
	20.00	31.95	26.75
ΔK_{\max}	24.05	44.25	
	27.72		67.05
	21.83		73.13

Figure 4. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the L-T Orientation

CONDITION/HT: T8

FORM: 0.50 in. thick plate

SPECIMEN TYPE: C(T)

SPECIMEN THICKNESS: 0.494-0.497 in.

ORIENTATION: L-T

SPECIMEN WIDTH: 3.999-4.003 in.

FREQUENCY: 15 HZ

ENVIRONMENT: 200°F, Lab Air

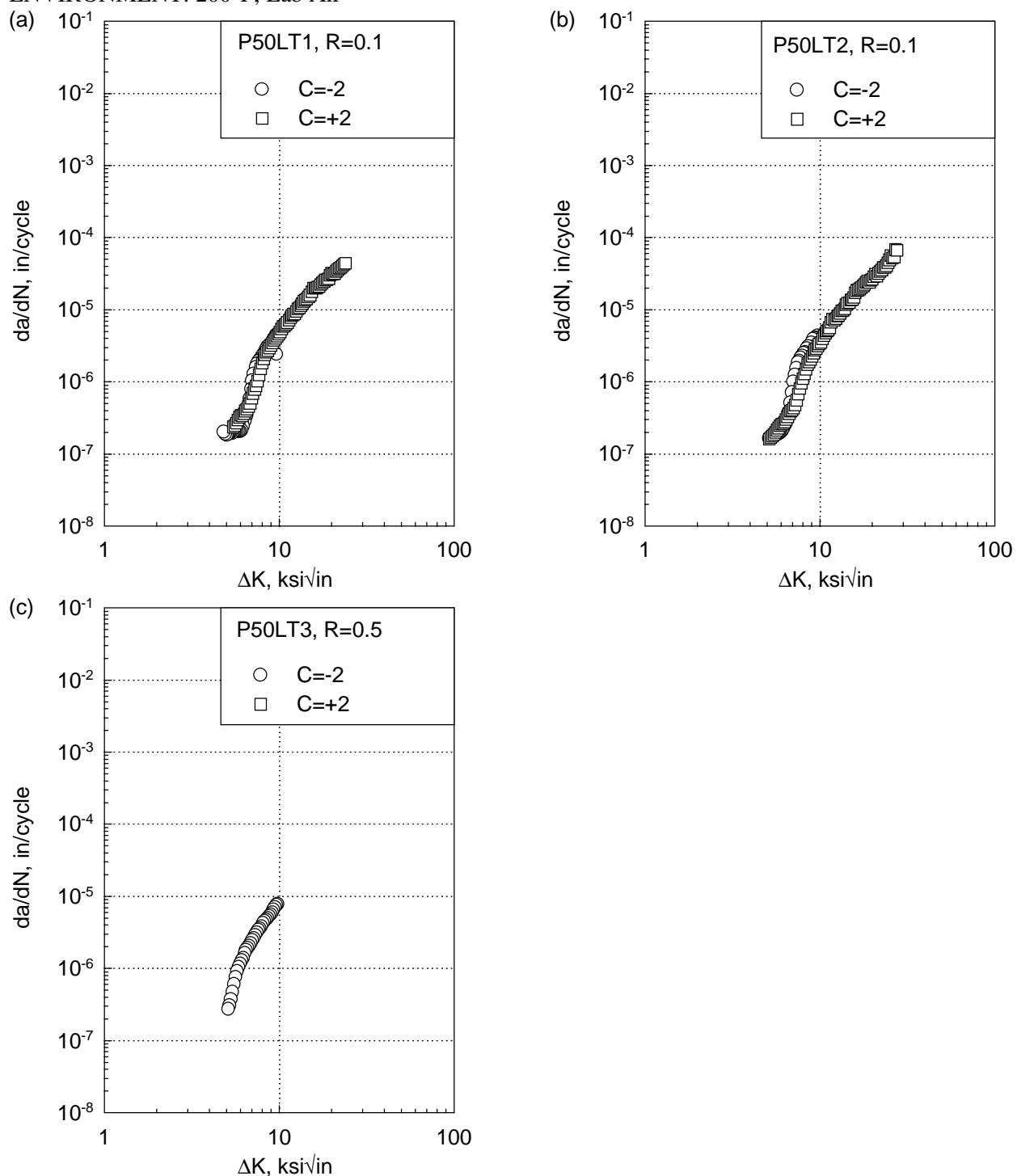


Table 5. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the T-L Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 5 Indicating Effect of Stress Ratio

Material: Aluminum 2195

Condition: T8

Environment: 200°F, Lab Air

	ΔK (ksi/in)	da/dN (10^{-6} in/cycle)		
		(a) P50TL1	(b) P50TL2	(c) P50TL3
		R=0.1	R=0.1	R=0.5
ΔK_{\min}	5.16	0.16		
	5.16		0.16	
	5.16			0.18
ΔK	6.00	0.25	0.25	0.28
	7.00	0.44	0.36	1.04
	8.00	0.97	0.56	2.31
	9.00	2.31	1.32	4.32
	10.00	3.79	2.42	6.37
	11.00	5.48	3.69	8.82
	12.00	7.42	5.64	11.97
	13.00	9.63	7.73	14.92
	14.00	12.13	9.79	18.57
	15.00	15.55	12.38	24.33
	16.00	19.85	17.21	36.52
	17.00	20.88	18.10	35.98
	18.00	25.83	20.78	46.84
	19.00	30.25	23.20	58.68
	20.00	33.54	28.06	70.30
ΔK_{\max}	26.58	74.44		
	27.25		65.94	
	24.16			216.99

Figure 5. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the T-L Orientation

CONDITION/HT: T8

FORM: 0.50 in. thick plate

SPECIMEN TYPE: C(T)

SPECIMEN THICKNESS: 0.493-0.494 in.

ORIENTATION: T-L

SPECIMEN WIDTH: 3.999-4.003 in.

FREQUENCY: 15 HZ

ENVIRONMENT: 200°F, Lab Air

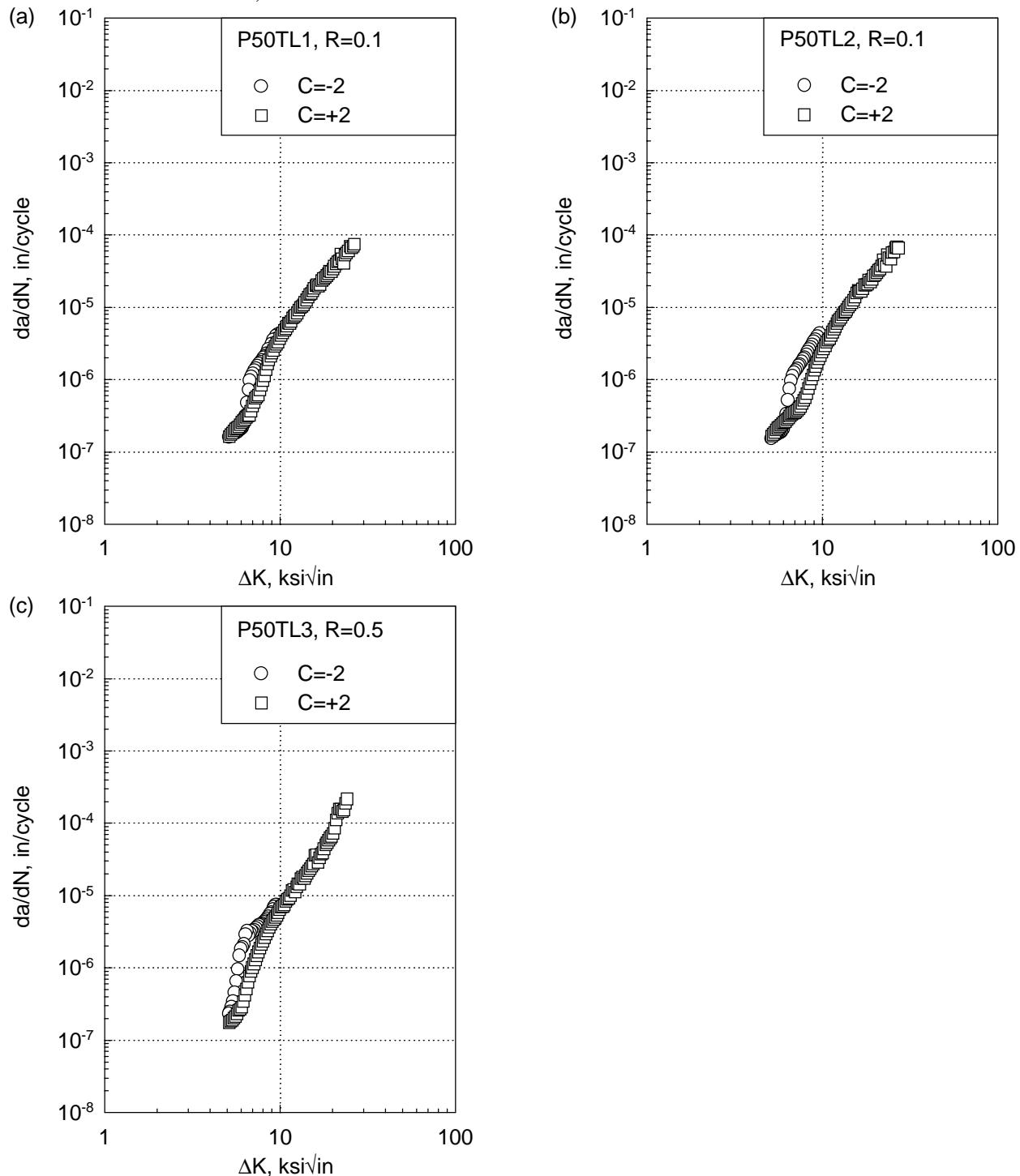


Table 6. Effect of Temperature on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the L-T Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 6 Indicating Effect of Temperature

Material: Aluminum 2195

Condition: T8

Environment: Lab Air

Stress Ratio (R): 0.5

ΔK (ksi $\sqrt{\text{in}}$)	da/dN (10^{-6} in/cycle)	
	(a) P50LT3	(b) P50LT4
		200°F
ΔK_{\min}	5.16	0.27
	5.16	0.55
	6.00	0.78
	7.00	2.16
	8.00	3.62
	9.00	5.50
	10.00	7.30
	11.00	9.76
	12.00	12.08
	13.00	14.91
	14.00	18.36
	15.00	21.65
	16.00	26.65
	17.00	32.43
	18.00	37.10
	19.00	43.88
	20.00	51.68
ΔK_{\max}	21.83	73.13
	24.65	135.39

Figure 6. Effect of Temperature on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the L-T Orientation

CONDITION/HT: T8

FORM: 0.50 in. thick plate

SPECIMEN TYPE: C(T)

ORIENTATION: L-T

FREQUENCY: 15 HZ

ENVIRONMENT: Lab Air

STRESS RATIO (R): 0.5

SPECIMEN THICKNESS: 0.497 in.

SPECIMEN WIDTH: 4.002-4.003 in.

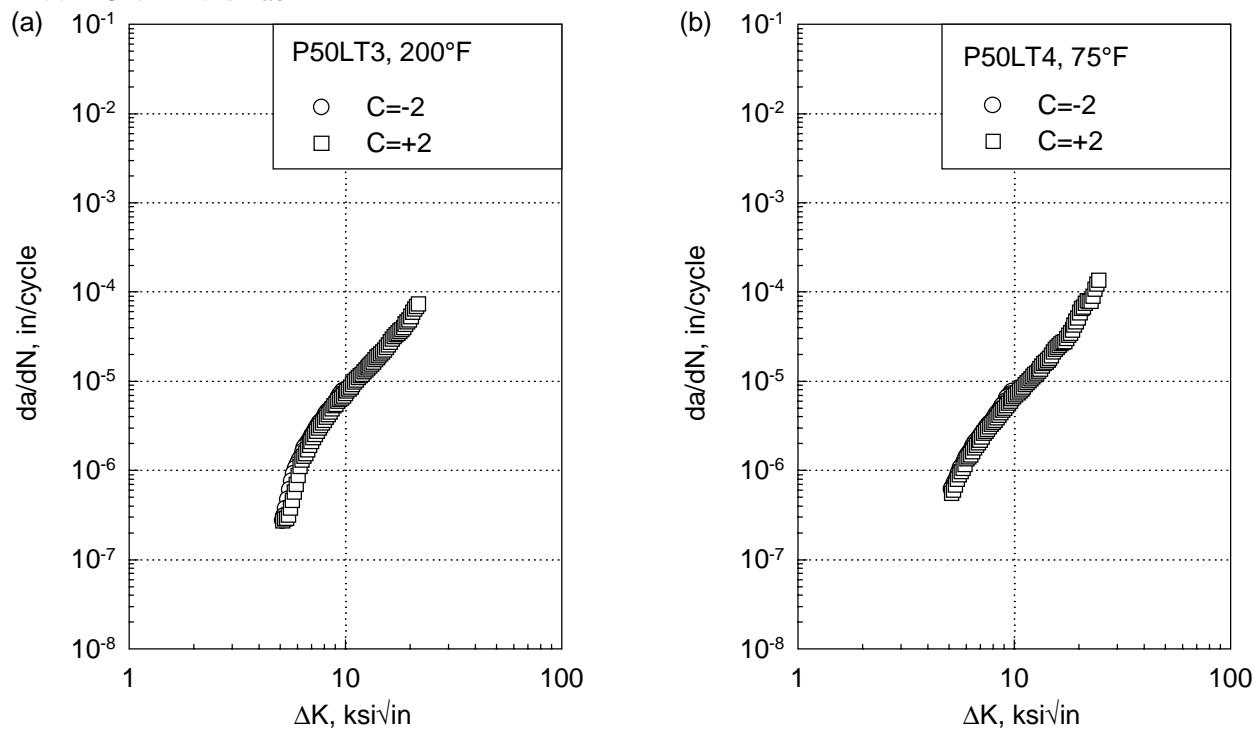


Table 7. Effect of Temperature on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the T-L Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 7 Indicating Effect of Temperature

Material: Aluminum 2195

Condition: T8

Environment: Lab Air

Stress Ratio (R): 0.5

ΔK (ksi $\sqrt{\text{in}}$)	da/dN (10^{-6} in/cycle)	
	(a) P50TL3	(b) P50TL4
		200°F
ΔK_{\min}	5.16	0.18
	5.16	0.41
	6.00	0.28
	7.00	1.04
	8.00	2.31
	9.00	4.32
	10.00	6.37
	11.00	8.82
	12.00	11.97
	13.00	14.92
	14.00	18.57
	15.00	24.33
	16.00	36.52
	17.00	35.98
	18.00	46.84
	19.00	58.68
	20.00	70.30
ΔK_{\max}	24.16	216.99
	24.19	170.27

Figure 7. Effect of Temperature on the Fatigue Crack Growth Rate in 0.50 in. AL-Li 2195-T8 Plate in the T-L Orientation

CONDITION/HT: T8

FORM: 0.50 in. thick plate

SPECIMEN TYPE: C(T)

ORIENTATION: T-L

FREQUENCY: 15 HZ

ENVIRONMENT: Lab Air

STRESS RATIO (R): 0.5

SPECIMEN THICKNESS: 0.494-0.498 in.

SPECIMEN WIDTH: 3.999-4.003 in.

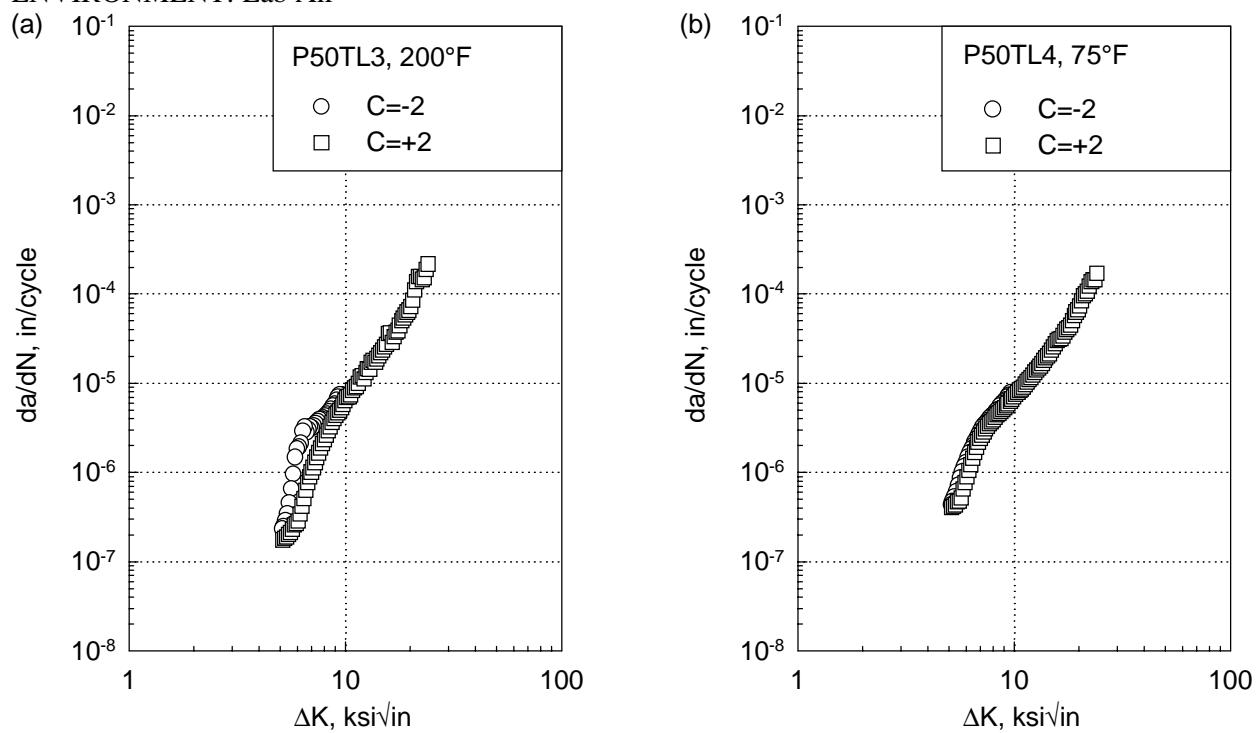


Table 8. Effect of Thickness on the Fatigue Crack Growth Rate in AL-Li 2195-T8 Plate in the L-T Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 8 Indicating Effect of Thickness

Material: Aluminum 2195

Condition: T8

Orientation: L-T

Environment: 200°F, Lab Air

Stress Ratio (R): 0.1

ΔK (ksi/in)	da/dN (10^{-6} in/cycle)			
	(a) P25LT2	(b) P25LT3	(c) P50LT1	(d) P50LT2
	0.25 in.	0.25 in.	0.50 in.	0.50 in.
5.16	0.24			
ΔK_{\min}	5.15	0.23		
	5.48		0.24	
	5.16			0.16
6.00	0.43	0.46	0.33	0.25
7.00	1.20	1.45	0.62	0.41
8.00	2.24	2.59	1.82	1.10
9.00	3.59	4.31	3.21	2.21
10.00	5.33	5.94	4.67	3.42
11.00	7.00	8.04	6.41	5.05
12.00	9.02	10.50	8.59	7.30
13.00	11.33	13.19	10.55	8.68
14.00	13.63	15.56	13.38	10.96
15.00	15.47	18.53	15.83	13.31
16.00	17.95	21.55	19.92	17.50
17.00	19.82	19.82	21.23	19.51
18.00	22.50	27.64	24.53	22.21
19.00	24.89	31.77	26.27	24.53
20.00	28.20	35.00	31.95	26.75
ΔK_{\max}	24.09	40.34		
	24.08		52.01	
	24.05			44.25
	27.72			67.05

Figure 8. Effect of Thickness on the Fatigue Crack Growth Rate in AL-Li 2195-T8 Plate in the L-T Orientation

CONDITION/HT: T8

FORM: 0.25 in. and 0.50 in. thick plate

SPECIMEN TYPE: C(T)

ORIENTATION: L-T

FREQUENCY: 15 HZ

ENVIRONMENT: 200°F, Lab Air

STRESS RATIO (R): 0.5

SPECIMEN THICKNESS: 0.286 in., 0.494-0.496 in.

SPECIMEN WIDTH: 4.002-4.003 in., 3.999-4.003 in.

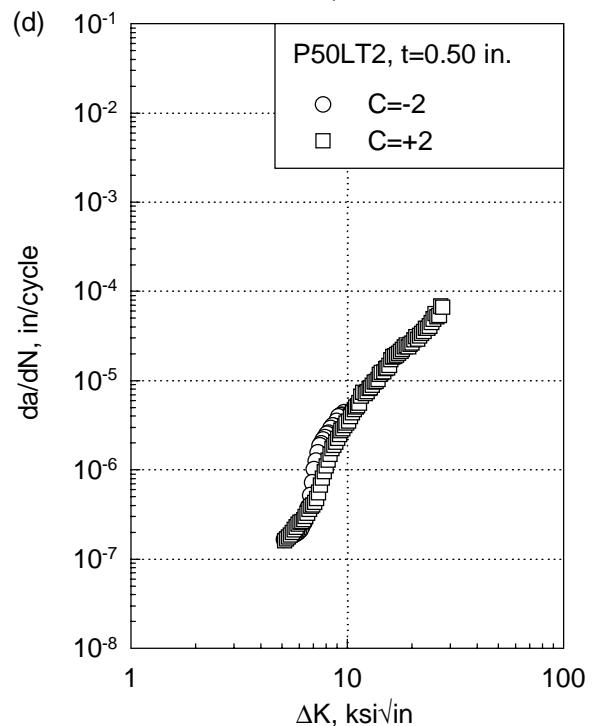
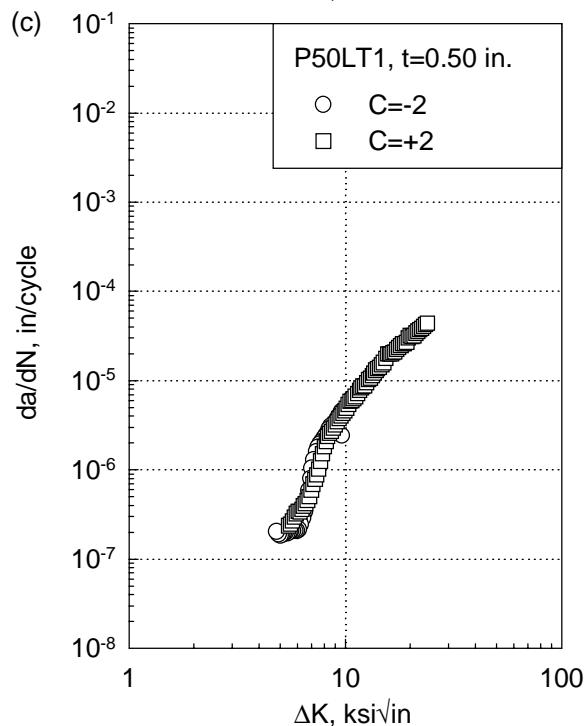
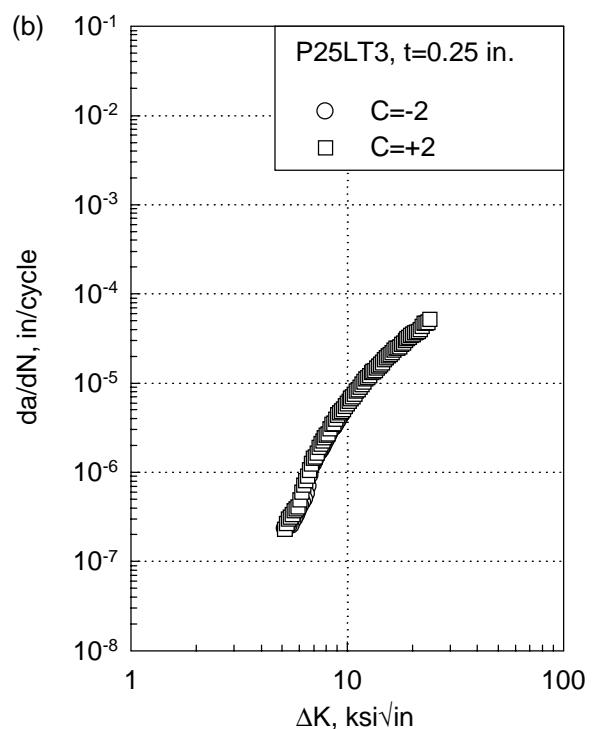
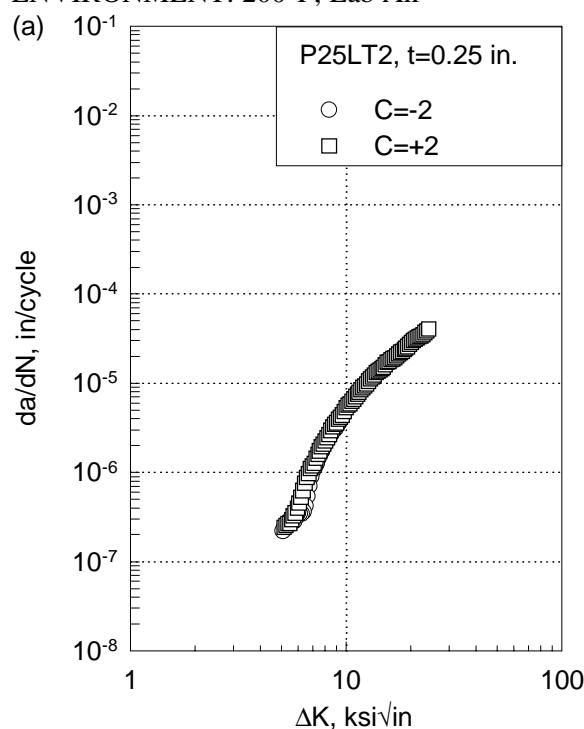


Table 9. Effect of Thickness on the Fatigue Crack Growth Rate in AL-Li 2195-T8 Plate in the T-L Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 9 Indicating Effect of Thickness

Material: Aluminum 2195

Condition: T8

Orientation: T-L

Environment: 200°F, Lab Air

Stress Ratio (R): 0.1

ΔK (ksi/in)	da/dN (10^{-6} in/cycle)			
	(a) P25TL5	(b) P25TL6	(c) P50TL1	(d) P50TL2
	0.25 in.	0.25 in.	0.50 in.	0.50 in.
5.07	0.21			
ΔK_{\min}	5.06	0.18		
	5.16		0.16	
	5.16			0.16
6.00	0.26	0.31	0.25	0.25
7.00	0.51	0.48	0.44	0.36
8.00	1.75	1.02	0.97	0.56
9.00	3.03	1.98	2.31	1.32
10.00	4.51	2.80	3.79	2.42
11.00	5.65	3.97	5.48	3.69
12.00	7.63	5.21	7.42	5.64
13.00	9.94	6.67	9.63	7.73
14.00	12.04	8.18	12.13	9.79
15.00	15.11	10.32	15.55	12.38
16.00			19.85	17.21
17.00			20.88	18.10
18.00			25.83	20.78
19.00			30.25	23.20
20.00			33.54	28.06
ΔK_{\max}	15.98	17.37		
	15.14		10.66	
	26.58			74.44
	27.25			65.94

Figure 9. Effect of Thickness on the Fatigue Crack Growth Rate in AL-Li 2195-T8 Plate in the T-L Orientation

CONDITION/HT: T8

FORM: 0.25 in. and 0.50 in. thick plate

SPECIMEN TYPE: C(T)

ORIENTATION: T-L

FREQUENCY; 15 HZ

ENVIRONMENT: 200°F, Lab Air

STRESS RATIO (R): 0.1

SPECIMEN THICKNESS: 0.270-0.271 in., 0.493-0.494 in.

SPECIMEN WIDTH: 4.001 in., 4.003 in.

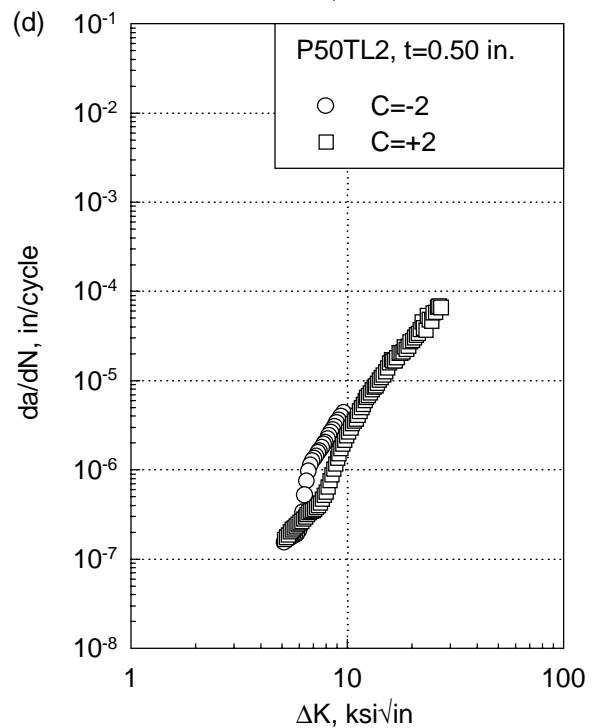
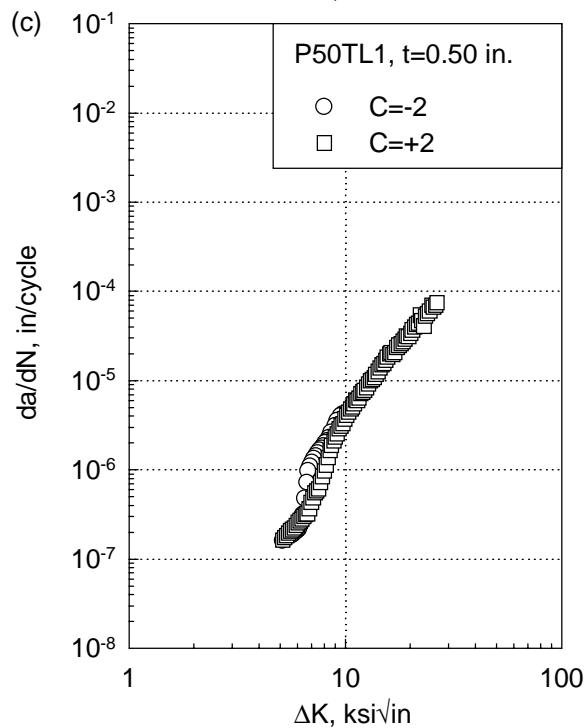
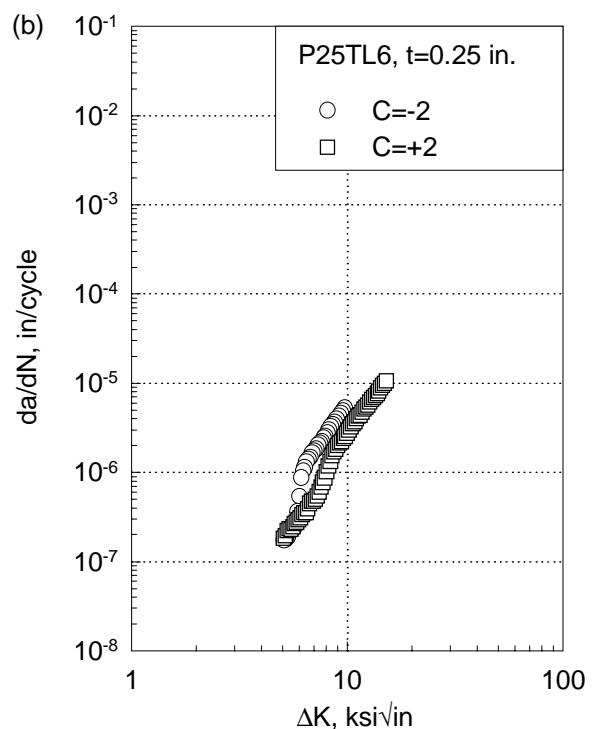
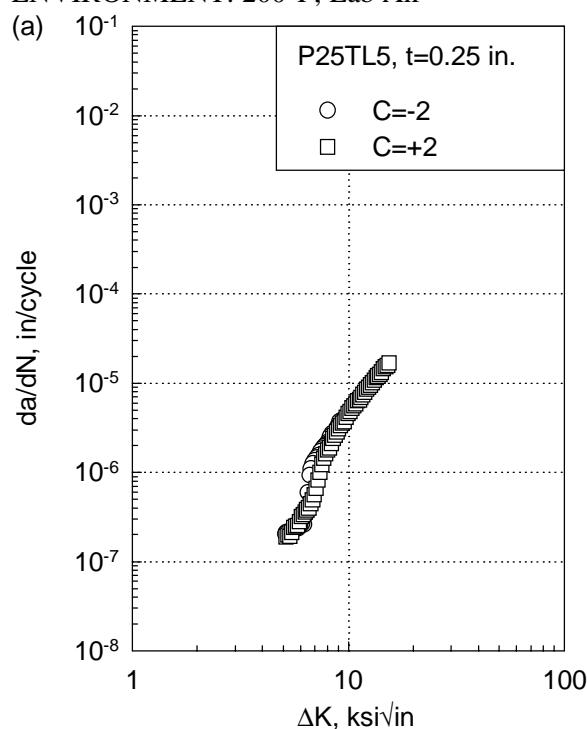


Table 10. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.25 in AL-Li 2195-T8 Variable Polarity Plasma Arc Welds in the L-T Orientation

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 10 Indicating Effect of Stress Ratio and Variable Polarity Plasma Arc Welding

Material: Aluminum 2195

Condition: T8, Variable Polarity Plasma Arc Welded

Environment: 75°F, Lab Air

ΔK (ksi \sqrt{in})	da/dN (10^{-6} in/cycle)		
	(a) 25PAW3	(c) 25PAW6	(d) 25PAW7
	R=0.1	R=0.5	R=0.5
ΔK_{min}	12.20	0.47	
	9.89		1.12
	8.63		0.13
ΔK	6.00		
	7.00		
	8.00		
	9.00		0.58
	10.00		1.62
	11.00		3.23
	12.00		6.28
	13.00	0.70	11.99
	14.00	0.78	56.38
	15.00	1.90	147.1
	16.00	3.69	326.4
	17.00	4.02	138.1
	18.00	4.84	333.4
	19.00	5.78	491.3
	20.00	8.18	971.9
ΔK_{max}	31.47	1075.3	
	20.28		1149.2
	20.06		1055.7

Figure 10. Effect of Stress Ratio on the Fatigue Crack Growth Rate in 0.25 in AL-Li 2195-T8 Variable Polarity Plasma Arc Welds in the L-T Orientation

CONDITION/HT: T8, WELDED

FORM: PAW 0.25 in. thick plate

SPECIMEN TYPE: C(T)

SPECIMEN THICKNESS: 0.217-0.219 in.

ORIENTATION: L-T

SPECIMEN WIDTH: 4.000-4.002 in.

FREQUENCY: 15 HZ

ENVIRONMENT: 75°F, Lab Air

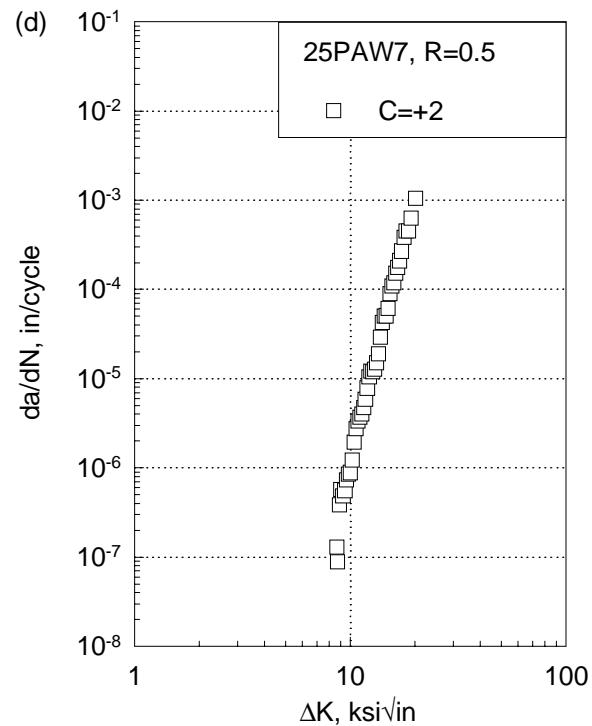
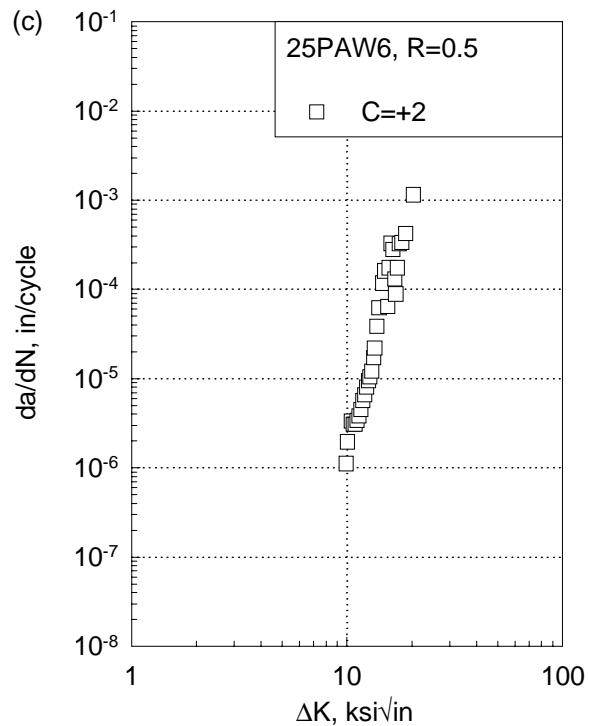
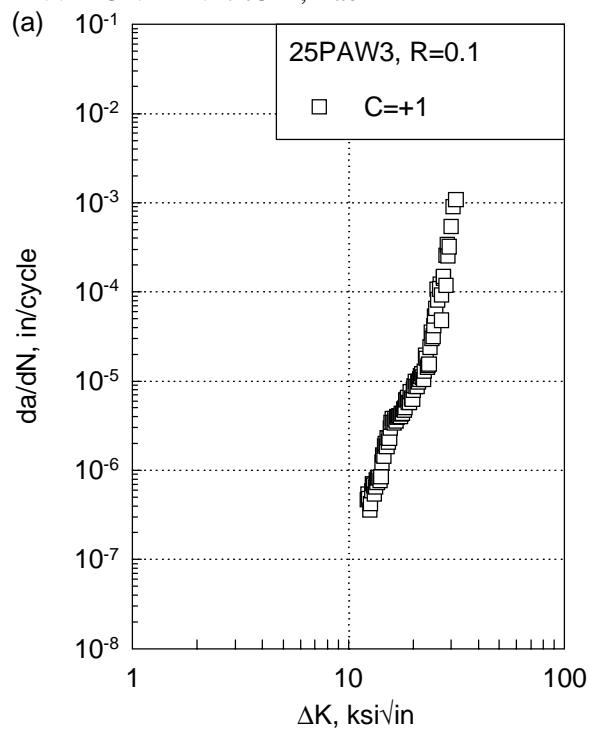


Table 11. Fatigue Crack Growth Rate in 0.25 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Ambient Temperature

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 11 Indicating Effect of Friction Stir Welding

Material: Aluminum 2195

Condition: T8, Friction Stir Welded

Environment: 75°F, Lab Air

ΔK (ksi/in)	$da/dN (10^{-6} \text{ in/cycle})$	
	(a) 25FSW2	(b) 25FSW5
	R=0.5	R=0.5
ΔK_{\min}	6.89 7.89	3.55 1.13
6.00		
7.00	1.38	
8.00	1.31	
9.00	3.11	7.16
10.00	5.08	7.18
11.00	7.15	8.24
12.00	11.49	13.50
13.00	11.82	11.00
14.00	13.21	12.69
15.00	14.87	14.57
16.00	17.54	17.25
17.00	20.52	19.83
18.00	23.56	23.65
19.00	27.26	27.34
20.00	31.19	28.02
ΔK_{\max}	20.02 21.93	31.38 29.78

Figure 11. Fatigue Crack Growth Rate in 0.25 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Ambient Temperature

CONDITION/HT: T8, WELDED
 FORM: FSW 0.25 in. thick plate
 SPECIMEN TYPE: C(T)
 ORIENTATION: L-T
 FREQUENCY: 15 Hz
 ENVIRONMENT: 75°F, Lab Air

STRESS RATIO (R): 0.5
 SPECIMEN THICKNESS: 0.209 - 0.213 in.
 SPECIMEN WIDTH: 3.999 - 4.001 in.

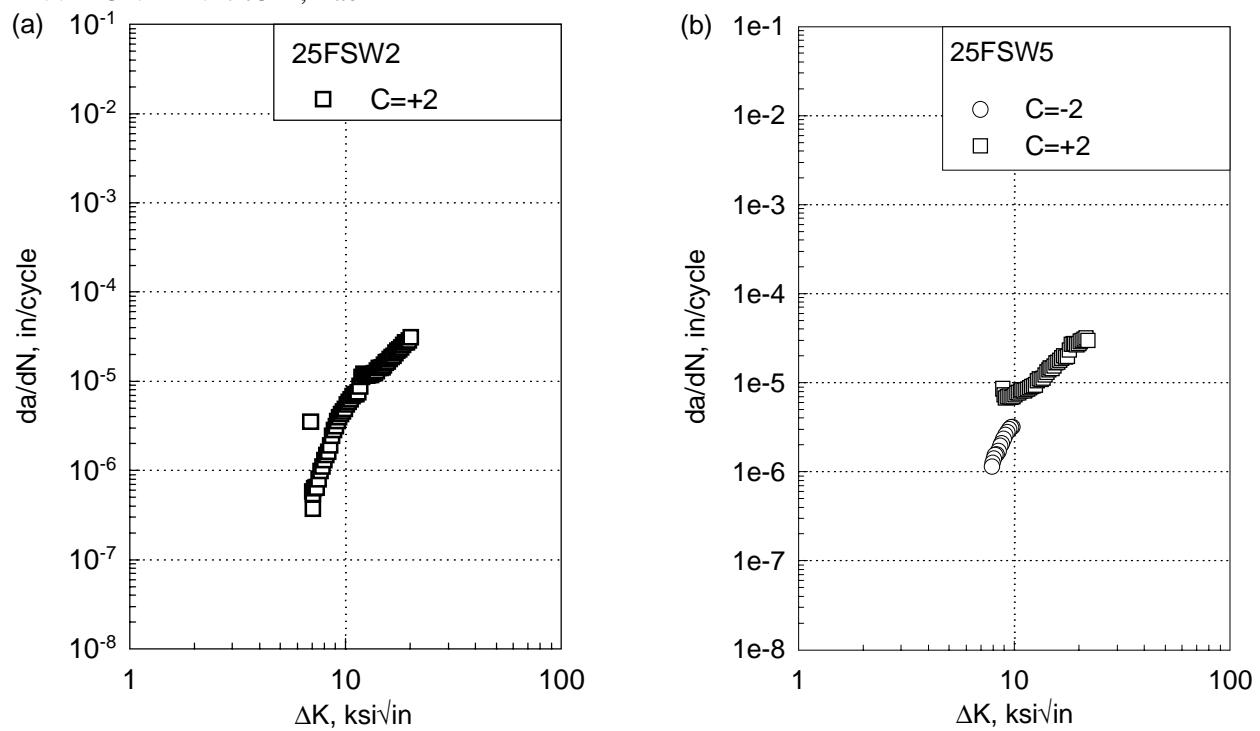


Table 12. Fatigue Crack Growth Rate in 0.25 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Cryogenic Temperature

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 12 Indicating Effect of Friction Stir Welding

Material: Aluminum 2195

Condition: T8, Friction Stir Welded

Environment: -320°F, LN₂

ΔK (ksi $\sqrt{\text{in}}$)		da/dN (10^{-6} in/cycle)
	(a)	
	25FSW6	
	R=0.5	
ΔK_{\min}	11.00	11.19
	6.00	
	7.00	
	8.00	
	9.00	
	10.00	
	11.00	11.19
	12.00	15.59
	13.00	19.41
	14.00	25.53
	15.00	31.93
	16.00	40.14
	17.00	46.96
	18.00	58.96
	19.00	69.93
	20.00	89.73
ΔK_{\max}	28.22	279.48

Figure 12. Fatigue Crack Growth Rate in 0.25 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Cryogenic Temperature

CONDITION/HT: T8, WELDED

FORM: FSW 0.25 in. thick plate

SPECIMEN TYPE: C(T)

ORIENTATION: L-T

FREQUENCY: 15 HZ

ENVIRONMENT: -320°F, LN₂

STRESS RATIO (R): 0.5

SPECIMEN THICKNESS: 0.209 in.

SPECIMEN WIDTH: 3.999 in.

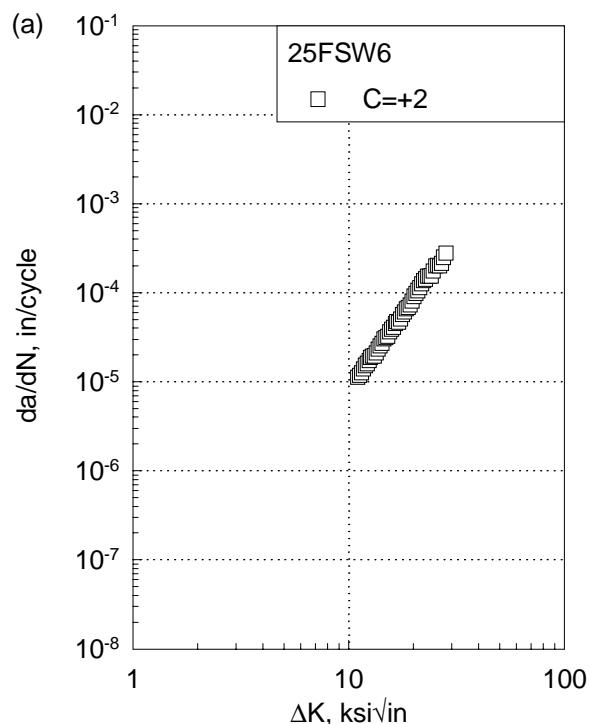


Table 13. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Elevated Temperature

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 13 Indicating Effect of Friction Stir Welding

Material: Aluminum 2195

Condition: T8, Friction Stir Welded

Environment: 200°F, Lab Air

ΔK (ksi/in)	$da/dN (10^{-6} \text{ in/cycle})$	
	(a) 50FSW1	(b) 50FSW4
	R=0.5	R=0.5
ΔK_{\min}	5.17	1.69
	5.17	1.44
	6.00	2.48
	7.00	4.21
	8.00	6.55
	9.00	9.06
	10.00	12.13
	11.00	15.28
	12.00	18.91
	13.00	22.78
	14.00	26.64
	15.00	30.90
	16.00	34.62
	17.00	
	18.00	
	19.00	
	20.00	
ΔK_{\max}	16.14	35.23
	15.86	35.84

Figure 13. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Elevated Temperature

CONDITION/HT: T8, WELDED
 FORM: FSW 0.50 in. thick plate
 SPECIMEN TYPE: C(T)
 ORIENTATION: L-T
 FREQUENCY: 15 HZ
 ENVIRONMENT: 200°F, Lab Air

STRESS RATIO (R): 0.5
 SPECIMEN THICKNESS: 0.471-0.476 in.
 SPECIMEN WIDTH: 4.000 in.

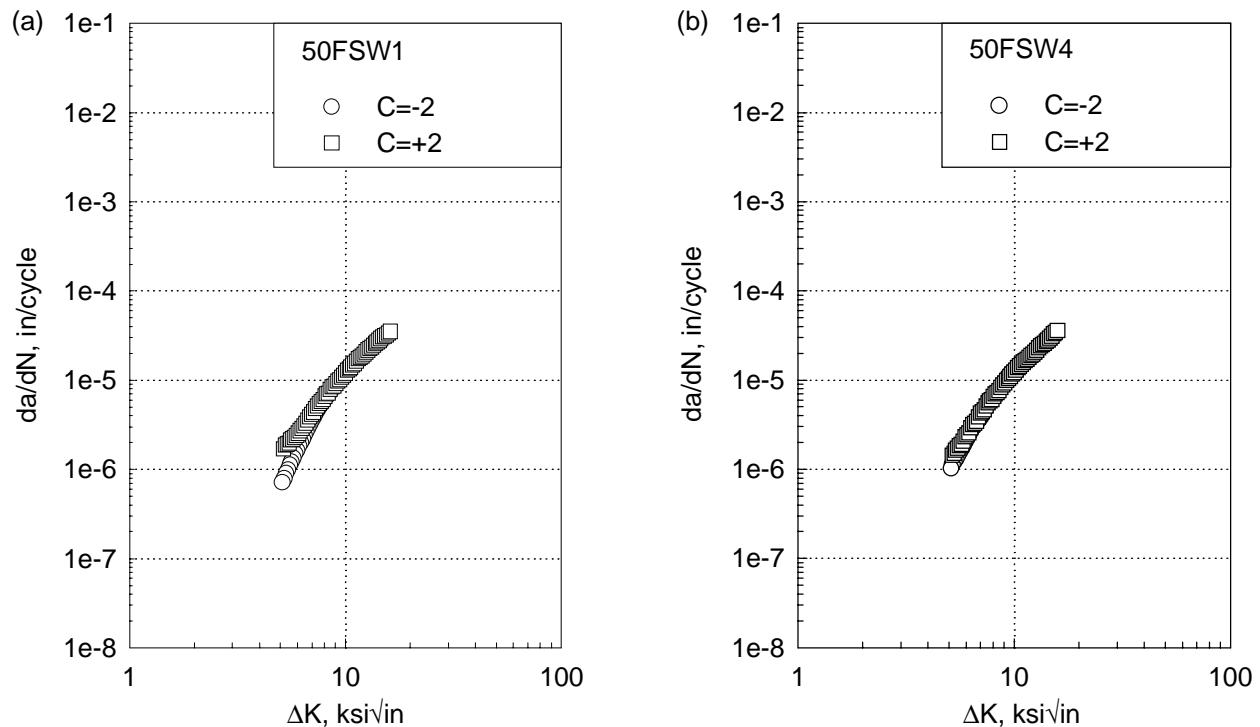


Table 14. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Ambient Temperature

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 14 Indicating Effect of Friction Stir Welding

Material: Aluminum 2195

Condition: T8, Friction Stir Welded

Environment: 75°F, Lab Air

ΔK (ksi $\sqrt{\text{in}}$)	da/dN (10^{-6} in/cycle)	
	(a) 50FSW2	(b) 50FSW5
	R=0.5	R=0.5
ΔK_{\min}	7.78 6.72	1.06 3.06
6.00		
7.00		1.24
8.00	1.43	6.35
9.00	12.46	7.62
10.00	6.07	10.53
11.00	6.46	14.72
12.00	9.44	16.70
13.00	14.97	20.67
14.00	12.81	23.14
15.00	16.90	23.79
16.00	24.56	22.72
17.00	31.60	23.43
18.00	36.27	31.52
19.00	40.91	48.85
20.00		
ΔK_{\max}	19.67 19.69	42.12 49.15

Figure 14. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Ambient Temperature

CONDITION/HT: T8, WELDED

FORM: FSW 0.50 in. thick plate

SPECIMEN TYPE: C(T)

ORIENTATION: L-T

FREQUENCY: 15 HZ

ENVIRONMENT: 75°F, Lab Air

STRESS RATIO (R): 0.5

SPECIMEN THICKNESS: 0.477-0.478 in.

SPECIMEN WIDTH: 4.000-4.001 in.

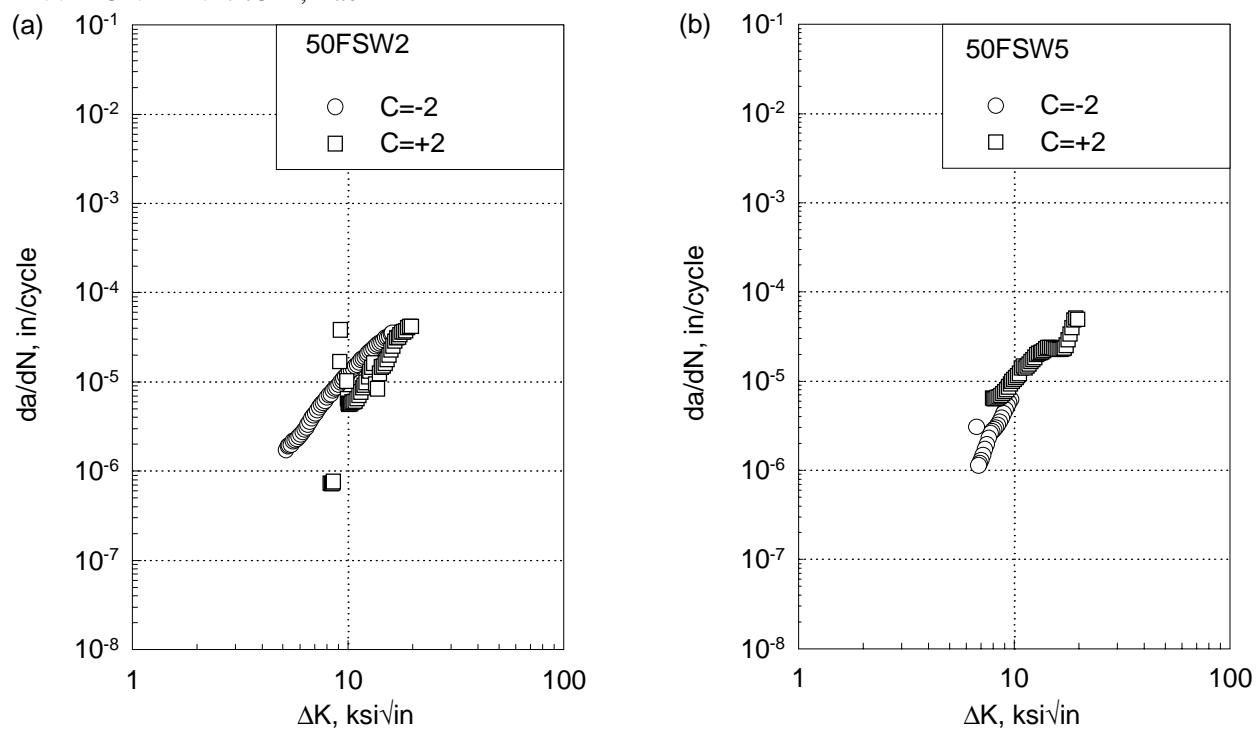


Table 15. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Cryogenic Temperature

Fatigue Crack Growth Rates at Defined Levels of Stress Intensity Factor Taken From K-Increasing Curve

Data Associated with Figure 15 Indicating Effect of Friction Stir Welding

Material: Aluminum 2195

Condition: T8, Friction Stir Welded

Environment: -320°F, LN₂

ΔK (ksi/in)	da/dN (10^{-6} in/cycle)	
	(a) 50FSW3	(b) 50FSW6
	R=0.5	R=0.5
ΔK_{\min}	10.33 9.46	6.85 1.71
	6.00	
	7.00	
	8.00	
	9.00	
	10.00	13.46
	11.00	9.34 11.19
	12.00	13.50 15.30
	13.00	19.51 21.41
	14.00	26.91 29.33
	15.00	36.17 40.24
	16.00	47.54 50.50
	17.00	59.28 63.07
	18.00	70.93 78.45
	19.00	80.17 89.66
	20.00	92.07 103.90
ΔK_{\max}	21.22 21.53	113.03 141.77

Figure 15. Fatigue Crack Growth Rate in 0.50 in. Al-Li 2195-T8 Friction Stir Welds in the L-T Orientation at Cryogenic Temperature

CONDITION/HT: T8, WELDED
 FORM: FSW 0.50 in. thick plate
 SPECIMEN TYPE: C(T)
 ORIENTATION: L-T
 FREQUENCY; 15 HZ
 ENVIRONMENT: -320°F, LN₂

STRESS RATIO (R): 0.5
 SPECIMEN THICKNESS: 0.477-0.478 in.
 SPECIMEN WIDTH: 4.000 in.

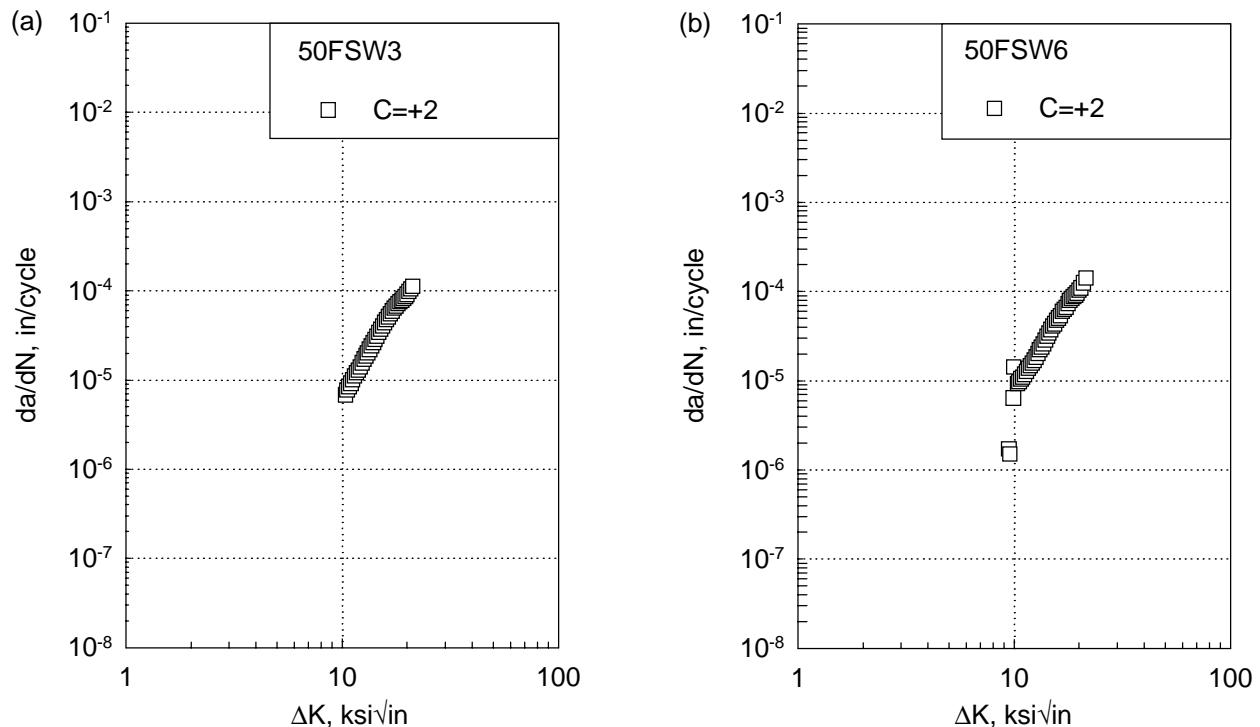


Table 16. Fatigue Crack Growth Rate, da/dN (10^{-6} in/cycle), for Al-Li 2195-T8 Plate and Weldments

Condition	t, in.	Orientation	R	Test Temp., °F	ΔK , ksi $\sqrt{\text{in}}$			Specimen ID	
					6	10	20		
2195-T8 Plate	0.25	L-T	0.1	75	0.42	3.91	30.70	P25LT1	
				200	0.43	5.33	28.20	P25LT2	
					0.46	5.94	35.00	P25LT3	
		T-L	0.1	200	0.26	4.51	N/A	P25TL5	
					0.31	2.80	N/A	P25TL6	
		T-L	0.5	200	1.09	N/A	N/A	P25TL7	
					1.36	N/A	N/A	P25TL8	
				200	0.33	4.67	31.95	P50LT1	
	0.50	L-T	0.1	200	0.25	3.42	26.75	P50LT2	
				75	1.26	6.79	55.74	P50LT4	
			0.5	200	0.78	7.30	51.98	P50LT3	
		T-L	0.1	200	0.25	3.79	33.54	P50TL1	
					0.25	2.42	28.06	P50TL2	
			0.5	75	0.84	7.09	71.04	P50TL4	
				200	0.28	6.37	70.30	P50TL3	
VPPAW	0.25	L-T	0.1	75	N/A	N/A	8.18	25PAW3	
			0.5	75	N/A	1.62	971.9	25PAW6	
					N/A	0.90	1029.7	25PAW7	
	0.25	L-T	0.5	-320	N/A	N/A	89.73	25FSW6	
FSW	0.25	L-T		75	N/A	5.08	31.19	25FSW2	
					N/A	7.18	28.02	25FSW5	
					N/A	N/A	92.07	50FSW3	
		L-T	0.5	-320	N/A	13.46	103.9	50FSW6	
					N/A	6.04	N/A	50FSW2	
				75	N/A	10.53	N/A	50FSW5	
	0.50	L-T		200	2.48	12.13	N/A	50FSW1	
					2.37	12.29	N/A	50FSW4	

Table 17. Summary of Fatigue Crack Growth Rate, da/dN (10^{-6} in/cycle), for Al-Li 2195-T8 Plate and Weldments

Condition	t, in.	Orientation	R	Test Temp., °F	ΔK , ksi $\sqrt{\text{in}}$			Specimen ID
					6	10	20	
2195-T8 Plate ¹	0.25, 0.50	L-T, T-L	0.1, 0.5	75	0.42 – 1.26	3.91 – 7.09	30.70 – 71.04	All
				200	0.25 – 1.36	2.42 – 7.30	26.75 – 70.30	All
VPPAW ¹	0.25, 0.50	L-T	0.1, 0.5	75	N/A	0.90 – 1.62	8.18 – 1029.7	All
FSW ¹	0.25, 0.50	L-T	0.5	-320	N/A	13.46	89.73 – 103.9	All
				75	N/A	5.08 – 10.53	31.19	All
				200	2.37 – 2.48	12.13 – 12.29	N/A	All
2195 (ref. 2) ²	0.25, 1.25	All	0.1, 0.5	-320	N/A	0.4 - 4	10 - 100	All
				75	0.06 – 15.0	0.2 - 50	N/A	All

1 – summary of results from this study

2 – summary of results from SLWT design allowables program

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